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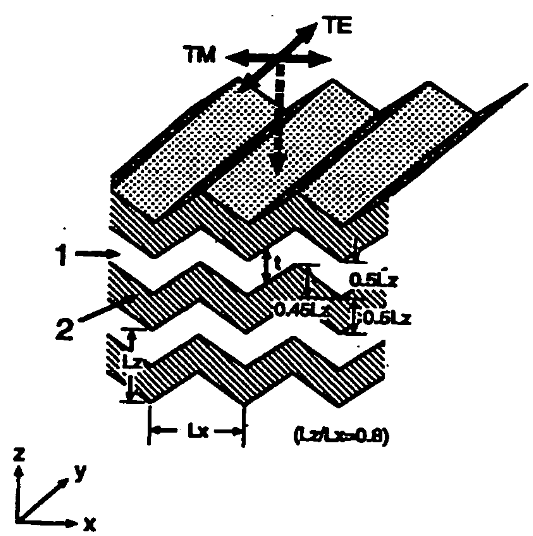
(54) POLARIZER

(57) The present invention provides a polarizer which has a two-dimensional periodic structure with has a pitch of 1 μm or so or less.

The polarizer has structure in which two or more film-shaped materials which have substantially regular periodic one-dimensional undulation. The polarizer has substantially regularly arranged two-dimensional periodic structure. For example, the polarizer consists of materials 1 and 2 which have different refractive indexes.

A regularly arranged two-dimensional structure which has a pitch of 1 μm or so or less can be obtained by a simple method. Because of this structure, the polarizer transmits the incidence light which has a specific polarization plane and reflects the incidence light which has a polarization plane which is orthogonalized to the plane.

Fig.1



EP 1 103 829 A1

Description

TECHNICAL FIELD

[0001] The present invention relates to a polarizer for use in optical instruments utilizing the polarization phenomenon that is a property of the light, the polarizer permitting only the linearly polarized light in a specific direction to be transmitted therethrough but reflecting the linearly polarized wave in a direction orthogonal thereto.

BACKGROUND ART

[0002] 'Polarizer' is an element which transmits only the light component which vibrates to a specific direction among the non-polarized light or elliptically polarized light whose electric and magnetic field vibrates to non-specific directions to give the linearly polarized light. It is one of the most fundamental optical elements, and is widely used as a device for the optical communication, a pick-up for the optical disc, a liquid crystal display, applied optical measurements, and so on. Operation modes of it can be roughly grouped into the following two modes: 1) the mode in which unnecessary polarized waves are absorbed, and 2) the mode in which two orthogonalized and polarized wave components which are emitted through the same light path are separated into different light passes. Depending on the purpose of utilizing a polarizer, the polarizer is required to have large aperture area, high performance, and so on or to be thin. It is industrially important to be able to supply such a polarizer inexpensively.

[0003] Presently a polarizer for general and practical use was prepared by doping a polymer film with a dichroic molecule such as iodine in the case of operation mode 1. Although this type of polarizer can be obtained inexpensively and in a large area, its extinction ratio and its temperature, stability are low, i.e., it has these faults.

[0004] In order to solve those problems, a polarizer prepared with materials having high stability has been developed, i.e., a polarizer prepared by arranging to one direction an absorber such as metal and semiconductor in a transparent body such as glass in minute lines or thin films. Polarized wave components which are parallel to the minute lines or thin films are absorbed or reflected, and polarized waves which are orthogonal to them are transmitted. Although this type of polarizer can have a high extinction ratio, processes such as cutting and polishing might be necessary, i.e., it is difficult to reduce the production cost. In addition, it is difficult to produce a thin polarizer which has a large area.

[0005] On the other hand, a polarizer which is prepared with birefringent crystals for operation mode 2 is prepared by sticking two triangular prisms which are made of a material which has a large birefringences such as calcite. A typical polarizer of this type is Gran Thomson prism. Although this type of polarizer can have generally a high extinction coefficient and transmittance, it is difficult to produce a polarizer which has a large area or a thin one. The material is expensive, so that the cost is high.

[0006] Polarizers utilizing Brewster angle of a transparent body include a polarized beam splitter using dielectric multilayer. Although it is inexpensive because it can be easily mass-produced, it has, at least the following problems: high polarization is not obtained; miniaturization is difficult; and wavelength band for use is narrow. Therefore, it is used only for limited purposes.

[0007] Each of the above-mentioned polarizers is practically used. On the other hand, very recently, a polarizer is theoretically proposed which utilizes anisotropy of propagation property of transparent periodic structure which has a pitch of the wavelength or shorter (Tetsuko Hamano, Masayuki Izutsu, and Hideki Hirayama "Possibility of polarizer using photonic crystal" Extended Abstracts of the Japan Society of Applied Physics, the 58th Autumn meeting, paper 2a-W-7, 1977; Akira Sato and Masahiro Takebe "Optically anisotropic multilayer by form birefringence film by structural double refraction" Optics Japan '97 Extended abstracts, paper 30pD01, 1997). These polarizers have the structure in which thin pillars of a transparent body with a refractive index is different from the host material are arranged two-dimensionally and regularly in a transparent host material. If the structure satisfies a condition that the pitch is, for example, half-wave length or so, among polarized waves which is parallel and vertical to those pillars, one can be transmitted, and the other can be blocked, i.e., it can work as a polarizer. Actually, however, any method for industrially constructing such structure has not been found, and any experimental example has not been reported.

[0008] The present invention was conceived to solve the above-mentioned problems. The object of the present invention is to provide a polarizer which has an excellent extinction ratio and insertion loss property and can has a large aperture area in spite of a small optical path length, and allows inexpensive industrial production.

DISCLOSURE OF THE INVENTION

[0009] Background technologies concerning the polarizer of the present invention will be described below. In artificially and regularly arranged structure comprising of a more refractive medium and a less refractive medium, each of two polarized wave components which are orthogonal to each other has an independent dispersion relation (relation between frequency and wave vector). These two polarized wave components are called TE and TM waves depending on which, electric field or magnetic field, is parallel to the longitudinal direction in the two-dimensionally and regularly arranged structure which is closely related to the

present invention. Also in the general three-dimensionally and regularly arranged structure, eigen modes are normally grouped into TE-like and TM-like waves. Therefore, these waves are also designated TE and TM waves for convenience in the present invention. TE and TM waves have different band gaps each if which is a frequency band at which the light is not transmitted. At a frequency band, one polarized mode may be blocked while another polarized mode may be a transmitted wave. Namely, at this frequency band, this regularly arranged structure can work as a polarizer which reflects or diffracts one polarized light and transmits another polarized light. In addition, a polarizer which has a sufficiently high extinction ratio is obtained by increasing the number of the period.

[0010] The present invention is based on 1) the finding of the existence of properties of the plane-type polarizer in the structure which consists of two or more transparent bodies which have different refractive indexes, wherein the shape of the layer which is a unit of lamination has a regularly arranged structure along x-axis, is uniform along y-axis, or has a longer pitch than along x-axis, and each layer is laminated along z-axis keeping each shape, in the three-dimensional rectangular coordinate system (x,y,z), i.e., in the structure in which two or more thin films which have regularly arranged pleats (undulation) are laminated, and 2) the finding of the method for constructing the regularly arranged structure which the applicants have been developed. The light is launched vertically or slantwise to the plane. The aperture area depends on the size of the substrate, so that it is quite easy to enlarge the aperture area. On the other hand, although the optical path length depends on the lamination thickness, a sufficient optical path length is several times of the wavelength (several μm) or so, so that the polarizer according to the present invention can be made thinner approximately by some digit than conventional polarizers.

[0011] On the other hand, in the method, represented by bias sputtering, for forming a film using both the diffuse incidence of depositing particles and spatter-etching, it is possible to laminate with repeating the undulation of the surface by controlling each of the deposition and the etching. This mechanism can be explained by a combination at an appropriate ratio of the following three effects: 1) the effect in which the deposition rate is retarded in the concave part which becomes a shadow by the diffuse incidence of the depositing particles, 2) the effect in which the etching rate becomes the largest at a plane which gives a tilt angle between approximately 50°-60° in the spatter etching, and 3) the effect in which particles which were removed mainly by the spatter etching readhere to other places (Shojiro Kawakami, Takashi Sato, and Takayuki Kawashima "Mechanism of Shape-Formation fot 3D Periodic Nanostructures by Bias Sputtering" *The Transactions of the Institute of Electronics, Information and Communication Engineers* C-I, vol.J81-C-I, no.2, pp.108-109, Feb. 1998).

[0012] This technique allows periodic lamination of thin films comprising of two transparent materials on a substrate on which an array of grooves are arranged without laborious positioning, with repeating its undulation. Namely, by utilizing this technique, one can easily fabricate the polarizers of the present invention.

[0013] The present invention allows inexpensively providing a polarizer which has an excellent extinction ratio and insertion loss property, and/or has a large aperture area in spite of a small optical pass length inexpensively.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014]

Fig. 1 illustrates the structure of a polarizer of Embodiment 1;
Fig. 2 illustrates a substrate which has grooves on its surface;
Fig. 3a illustrates the intensity distribution of the transmitted light for TE wave in the near field;
Fig. 3b illustrates the intensity distribution of the transmitted light for TM wave in the near field;
Fig. 4 illustrates the relation between the frequency and the wave, motion, vector in Embodiment 2;
Fig. 5 illustrates the structure of a polarizer of Embodiment 2; and
Fig. 6 illustrates the relation between the frequency and the wave motion vector in Embodiment 2.

(Explanation of Reference Numerals)

[0015]

1 Si_2O layer
2 Si layer
3 Substrate
4 Anti-reflection coating layer
5 Periodic array of grooves
6 A frequency band at which a polarizer transmits TM wave
7 SiO_2 layer
8 Si layer

EMBODIMENT

[0016] Fig. 1 illustrates a polarizer of the present invention. A polarizer of the present invention will be described referring to Fig. 1 below.

[0017] A transparent medium which has a higher refractive index and a transparent medium which has a lower refractive index are alternately laminated on regularly arranged grooves or rows of linear projections keeping the shape of the interface. Polarizers in the following embodiments have periodic structures along x- and z-axes, and are uniform along y-axis. The operation

mechanism is similar even if the structure along y-axis is changed to have regularly or non-regularly arranged structure which has a length larger than x-axis. To the periodic structure thus obtained, non-polarized or elliptically polarized light is launched along z-axis. To polarized wave parallel to the groove row (y-polarized wave) and polarized wave orthogonal to the wave (x-polarized wave), TE mode and TM mode lights are generated in the periodic structure. If the frequency of the light is in a band gap of the TE mode or of the TM mode, the mode can not propagete in the periodic structure, so that the launched light is reflected or diffracted. On the other hand, the frequency of the light is in the energy band, the light is transmitted in the periodic structure keeping the wave vector. Therefore, it works as a plane-type polarizer.

[0018] In the polarizer of the persent invention, the wavelength band at which TE mode and TM mode band gaps are generated can be arbitrarily changed by controlling the pitch of the groove row (Lx) and the pitch of the direction of the lamination (Lz). Namely, it is possible to arbitrarily set the wavelength band at which the polarizer works.

[0019] In addition, as a low refractive index medium, a material containing SiO_2 as a main component is most popularly used. SiO_2 has a broad transparent wavelength region, and is chemically, thermally, and mechanically stable, and is easily deposited to a film. As a high refractive index material, an oxide such as TiO_2 and a semiconductor such as Si and GaAs can be used. TiO_2 and the like have a broad transparent wavelength range, so that they can be used also in a visible light region. On the other hand, although the semiconductor can be used only in a near infrared region, it has an advantage of a large refractive index.

[0020] It is desirable that the polarizer for many purposes can be used in a broad frequency band. The frequency band for the polarizer's operation can be set broad by appropriately determining the shapes of the high refractive index medium layer and the low refractive index medium layer. The degree of freedom in the shapes of the high refractive index medium layer and the low refractive index medium layer is large for monochromic light such as specific laser light, so that the shape can be selected which allows easy repetition in the formation of the film.

[0021] Shapes of the layers and the periodic structure, and methods for preparing them will be described in the following embodiments.

Embodiment 1

[0022] Fig. 1 illustrates the structure of a polarizer of Example 1. Fig. 1 illustrates amorphous SiO_2 layer 1 and amorphous Si layer 2. A pitch along x-axis (Lx) is 0.4 μm, and a pitch along z-axis (Lz) is 0.32 μm. SiO_2 and Si layers have shapes which were periodically, bent with slightly changing thickness 't'. A method for preparing the polarizer will be described below. First, periodically arranged grooves were prepared on a substrate by the electron beam lithography and the dry etching. Fig. 2 illustrates silica glass substrate 3, anti-reflection coating layer 4, and periodically arranged groove part 5. Although the constituent materials of the anti-reflection coating layer 4 and the periodic grooves part 5 are generally selected from the materials which are different from the substrate depending on the dimension of the periodic structure, they can also be the same material as the substrate. The latter case is provided in this example. The width of the groove is 0.4 μm, the depth of the groove is 0.2 μm, and the pitch of the groove to the horizontal direction is 0.4 μm. On this substrate, SiO_2 and Si layers were alternately laminated by the bias spattering method using targets of SiO_2 and Si. It is important to form films keeping regularly undulated form along x-axis of each layer. The condition was as follows: To form a film of SiO_2, an Ar gas pressure of 1.9 mTorr, applied RF power of 400W, and bias RF power of 60W. To form a film of Si, an Ar gas pressure of 3.6 mTorr and applied RF power of 400W. Ten SiO_2 layers and ten Si layers were laminated alternately.

[0023] The reason why the laminated structure shown by Fig. 1 is formed on the substrate which has rectangular grooves shown by Fig. 2 under the condition can be explained by a combination of two or more phenomena selected from the following three phenomena: 1) deposition by diffuse incidence of neutral particles, from the target, 2) spatter etching by vertical incidence of Ar ion, and 3) readhesion of deposited particles.

[0024] Figs. 3a and 3b illustrate an intensity distribution of the transmitted light for TE and TM waves at a wavelength of 1.0 μm in the near field in the periodic structure which was thus obtained. The abscissa is the position on a substrate wafer. The central part is a polarizer part. On both sides of the part, the substrate wafer does not have any groove, and parallel layers of Si and SiO_2 were deposited. The ordinate is the intensity of transmitted light at each point on a substrate wafer. It is clear that the polarizer part substantially blocked TE wave. On the other hand, for TM wave, the difference is minute between the intensity of the transmitted light in the film part which were deposited on a substrate which has no groove on both sides and that of the polarizer part. In other words, TM wave can be transmitted with minute loss by applying an anti-reflection coating on a polarizer part.

[0025] Fig. 4 illustrates the relation between the frequency and the wave vector in the periodic structure as calculated by the FDTD method (Finite Difference Time Domain method) using periodic boundary conditions. The analysis of the band structure and light transmission properties of a photonic crystal by the FDTD method was reported by S. Fan et al. (Physical Review B, vol. 54, no. 16, pp. 11245-11251 (1996)). In Fig. 4, the abscissa is a relative value of a magnitude of the wave vector, and the ordinate is a relative value of fre-

quency Lx/λ, wherein λ is a wavelength of the incident light, and k_z is a z-component of the wave vector. The solid and dashed lines are dispersion curves for TE and TM waves, respectively. $Lx = 0.4$ µm and $\lambda = 1$ µm give a frequency (Lx/λ) of 0.4. As understood from Fig. 4, the line $Lx/\lambda = 0.4$ does not cross the dispersion curve of TE wave (solid line), but crosses the dispersion curve of TM wave (dashed line). This means that TE wave is blocked/reflected, and that TM wave is transmitted. Namely, this periodic structure works as a polarizer which transmits TM wave in a frequency band 6 which has a frequency (Lx/λ) of 0.39-0.43.

Example 2

[0026] This example will illustrate that a polarizer is obtained which has excellent properties even if parameters such as the uniformity of the thickness of each dielectric layer in the plane, the shape of grooves, and an Lz/Lx ratio are different from those of Example 1.

[0027] Fig. 5 illustrates the constitution of other examples of the present invention including amorphous SiO_2 layer 7 and amorphous Si layer 8. A pitch along x-axis (Lx) is 0.4 µm, and a pitch along z-axis (Lz) is 0.32 µm. This polarizer has the structure in which SiO_2 and Si layers are regularly bent changing the thickness of SiO_2 layer between 0.9Lz and 0.3Lz, and changing the thickness of Si layer between 0.1Lz and 0.7Lz. To prepare the laminated films, although the same substrate was used as that of Embodiment 1, a different condition was used for bias spattering for forming SiO_2 and Si layers.

[0028] Fig. 6 illustrates the relation between the frequency and the wave vector in this periodic structure as calculated by the FDTD method. The abscissa is a relative magnitude of the wave vector, and the ordinate is a relative frequency. The solid and dashed lines are dispersion curves of TE and TM waves. As understood from Fig. 6, this polarizer has a wider frequency band to work as a polarizer than that of Embodiment 1. It is preferable that the frequency width of a band gap is wide also for a polarizer which is used at a single frequency of light in the band gap. Because at a frequency which is not sufficiently distant from the edge of the band gap, the number of the periods along z-axis which is necessary to have a sufficiently large extinction ratio increases.

[0029] In Embodiments 1 and 2, although a ratio of the pitch along z-axis to that of x-axis (Lz/Lx) is 0.8, from other calculations by the FDTD method, it is known that the polarizer works even at a ratio of 0.2 or so. Although the pitch along x-axis (Lx) is selected to be a wavelength of the light or less or so when used as a normal polarizer, it is known that it is good to select a pitch (Lx) which is longer than the wavelength of the light for a polarizing element which transmits one polarization component of the light and diffracts the other polarization component. It is also known from other calculations that grooves do not necessarily be uniform along y-axis, can have a different perariodicity with respect to the width and spacing of grooves along x-axis, or can have random lengths which are sufficiently long along y-axis.

[0030] Although the bias spattering method was used as means to repeatedly laminate unit layers in this Embodiment, the degree of freedom in designing the shape of the unit layer of the lamination can be enhanced by adding a method of performing the deposition process and the spattering process non-simultaneously. As a low refractive index medium, optical glass such as Pyrex glass can be used as well as amorphous SiO_2. As a high refractive index medium, TiO_2, Ta_2O_5, and the like can be used as well as Si. The cross-sectional shape of the groove of the substrate can be rectangular as well as V-shape. Various shapes of cross-section of groove can be formed by appropriately selecting the condition of bias spattering.

[0031] In order to use laminated films which were thus prepared as a polarizer, anti-reflection coatings are applied on the surface and the plane which is opposite to the substrate, and the obtained films are cut. Many elements can be prepared in a batch. In addition, polishing is not necessary, and cutting process is simple. As a result, polarizers can be provided inexpensively. The thickness of laminated films excluding substrate is several micrometers, so that the polarizer can be used for vertical incidence or for a small incidence angle with respect to the surface normal. Therefore, wide application is possible as a small isolator for optical communication and so on. When the polarizer is used as a polarization beam splitter for an optical circulator and so on, the polarizer might be used being inclined much with respect to the direction of incidence. Even in such a case, the light does not transmit the section, so that polishing is not necessary.

INDUSTRIAL APPLICABILITY

[0032] A polarizer of the present invention which is prepared by film-forming method including spattering-etching action has a minute thickness along the direction of transmission of the light, and can be prepared as large laminated films in one film-forming process. Polishing is not necessary and cutting is easy when each element is prepared. It is possible to design a polarizer which has excellent polarization properties corresponding to a wavelength region to be used. Such a polarizer is most suitable for an optical isolator. Such a polarizer can be widely industrially used, for example, as an optical circulator and an optical switch, and can be substituted for conventional polarizers.

Claims

1. A polarizer which has the multilayered structure along z-axis comprising of two or more transparent bodies which have different refractive indexes,

wherein the shape of layers which is the unit of lamination of each transparent body has regularly undulated structure along x-axis, is uniform along y-axis, or has regularly or non-regularly undulated structure which has a period longer than that of x-axis, and has lamination along z-axis repeating the shape, and functions for the light whose incident direction has non-zero z component in the three-dimensional orthogonal coordinates (x,y,z).

2. A polarizer according to claim 1 wherein the polarizer has a high refractive index medium layer containing Si or TiO_2 as a main component and a low refractive index medium layer containing SiO_2 as a main component.

3. A polarizer which was prepared by laminating a high refractive index medium and a low refractive index medium with regularly repeating the shape by a film-forming method at least partly including the dry etching on a substrate which has a periodic array of grooves or a peridic array of linear projections or thin and long projections or thin and long grooves.

4. A polarizer which was prepared by laminating a high refractive index medium which contains Si or TiO_2 as a main component and a low refractive index medium which contains SiO_2 as a main component with regularly repeating the shape by a film-forming method at least partly including the dry etching on a substrate which has a periodic array of grooves or a periodic array of linear projections or thin and long projections or thin and long grooves.

Fig.1

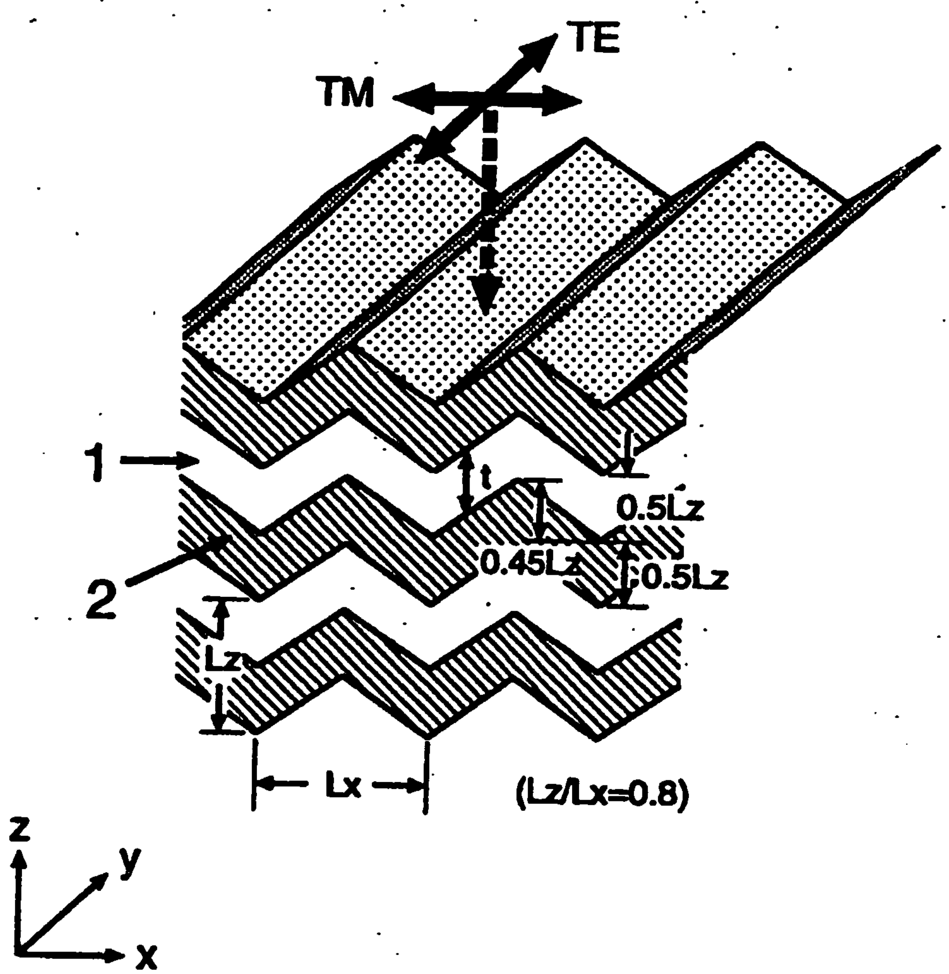


Fig. 2

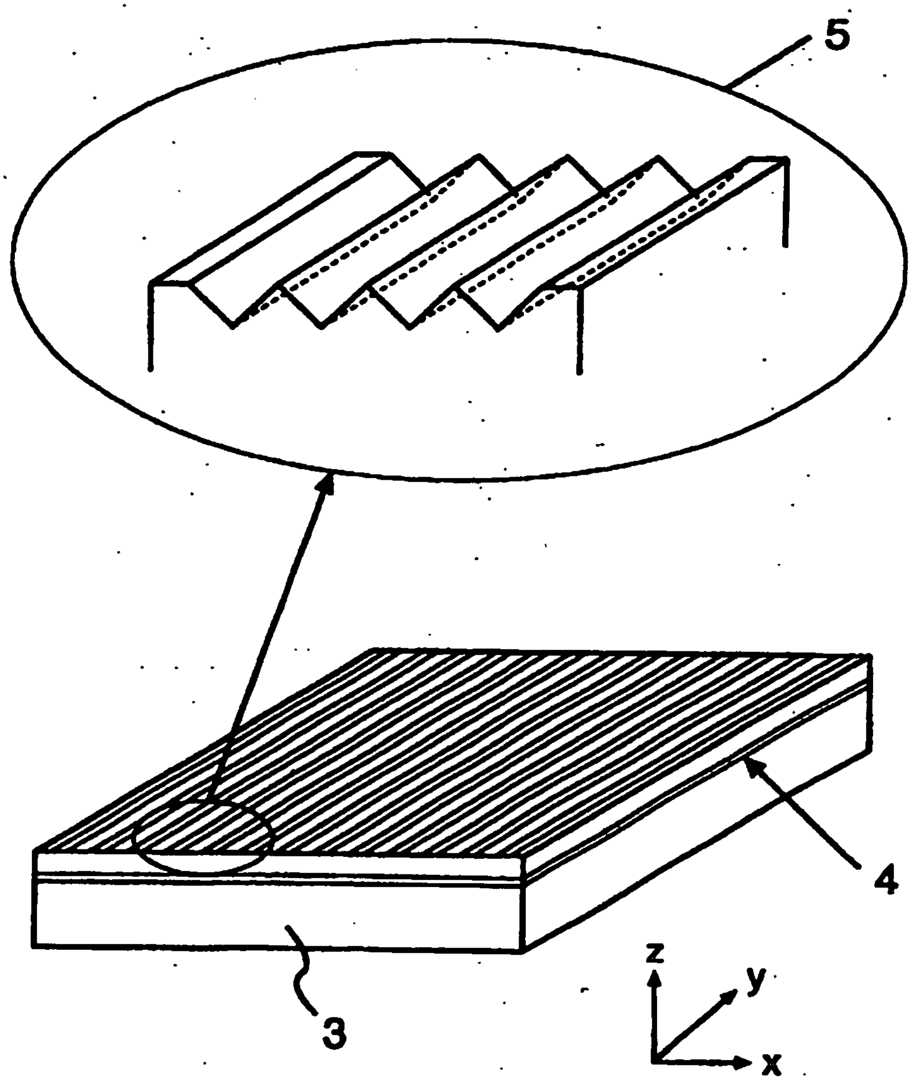
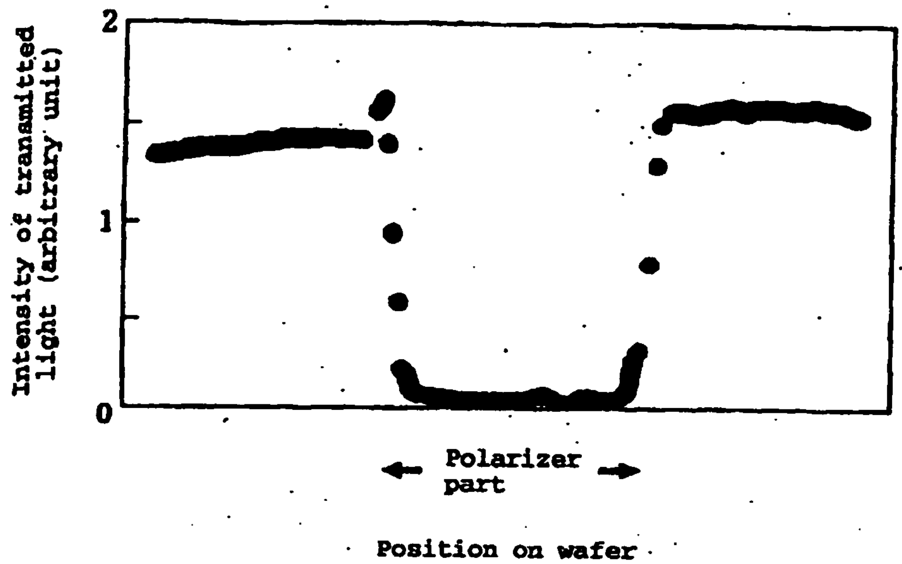


Fig.3

(a) TE wave



(b) TM wave

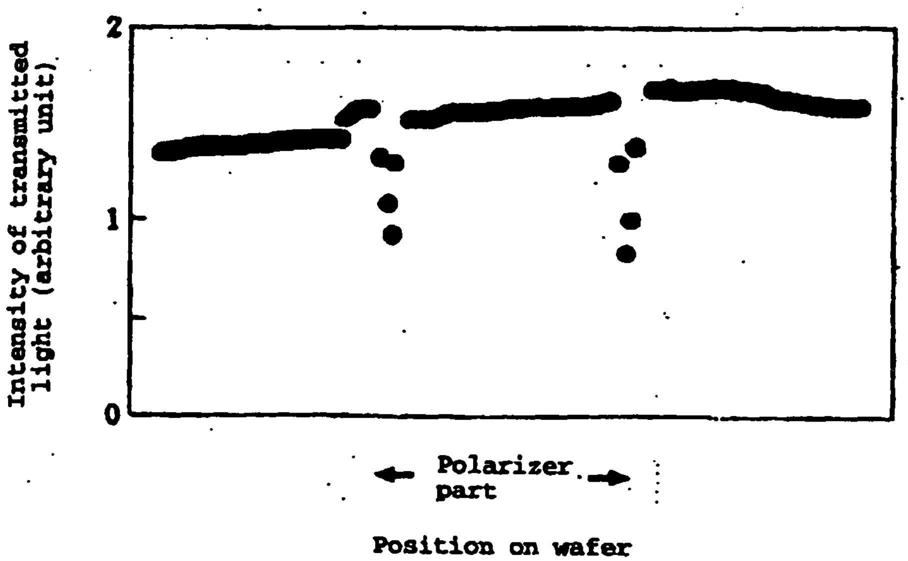


Fig.4

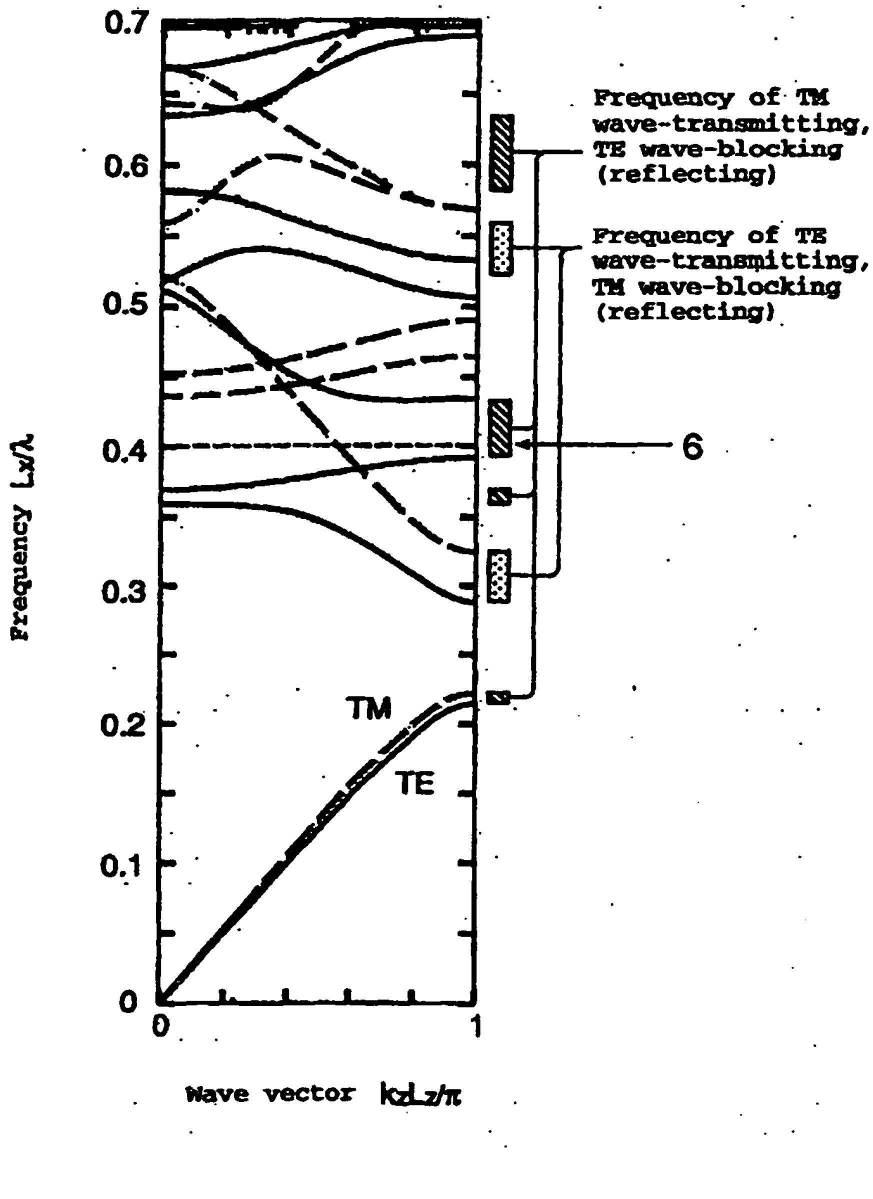

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
Frequency Lx/λ
Wave vector kzLz/π
TM
TE
6
Frequency of TM wave-transmitting, TE wave-blocking (reflecting)
Frequency of TE wave-transmitting, TM wave-blocking (reflecting)

Fig.5

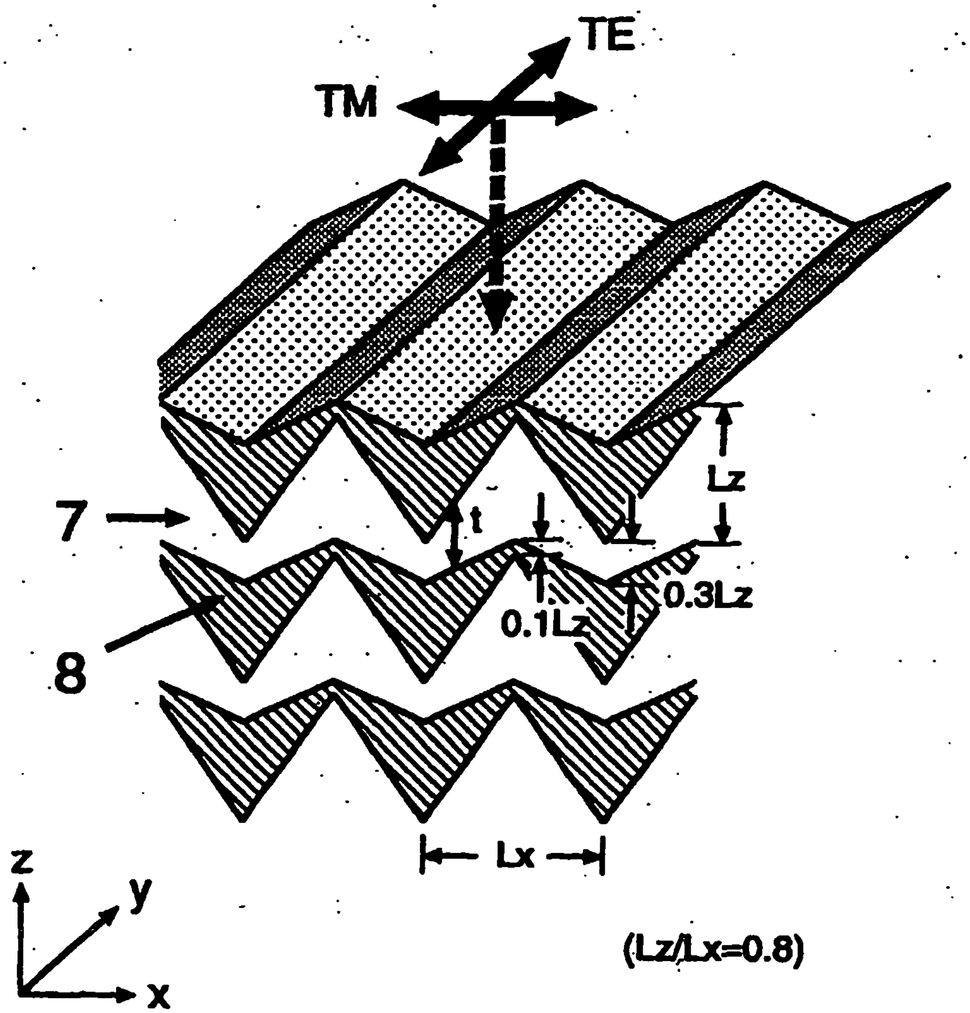
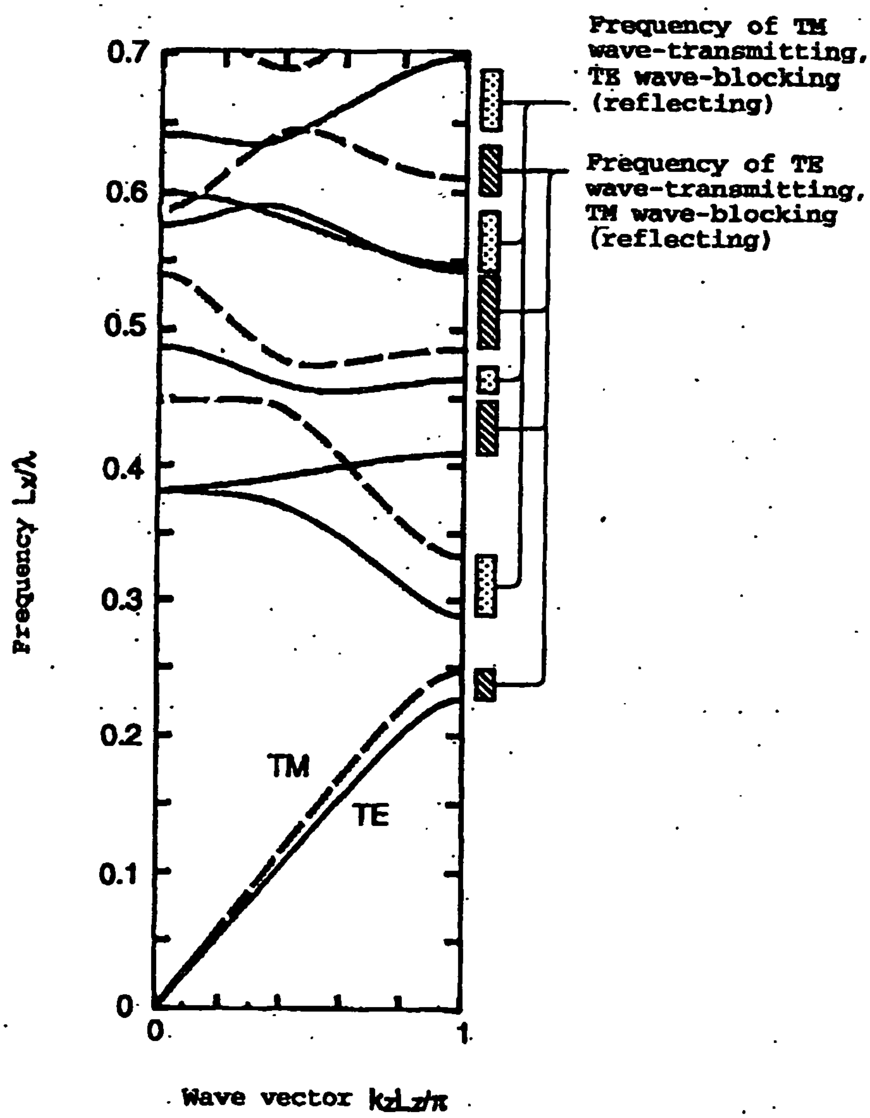


Fig.6


Frequency of TM wave-transmitting, TE wave-blocking (reflecting)
Frequency of TE wave-transmitting, TM wave-blocking (reflecting)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Frequency Lx/λ
TM
TE
0
1
Wave vector kzLz/π

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP99/04297

A. CLASSIFICATION OF SUBJECT MATTER
Int. Cl[6] G02B5/30, G02B5/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Int. Cl[6] G02B5/30, G02B5/18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1926-1996	Toroku Jitsuyo Shinan Koho	1994-1999
Kokai Jitsuyo Shinan Koho	1971-1999	Jitsuyo SHINAN Toroku Koho	1996-1999

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Extended Abstracts (The 58[th] Autumn Meeting, 1997); The Japan Society Of Applied Physics (October 1997), Tetsuko Hamano, Masayuki Ito, Hideki Hirayama, "Possibility of polarizer using 2D photonic crystals" paper 2a-W-7 (p.993)	1-4
Y	The Transactions of The Institute of Electronics, Information and Communication Engineers C-II, Vol.J80-C-II No. 6, (June 1997) Shojiro Kawakami et al., "Fabrication and observation of 3D photonic crystals composed of Si/SiO_2 with Sub-Micrometer periods" p.222-223	1-4
Y	JP, 9-304611, A (Oki Electric Ind. Co., Ltd.), 28 November, 1997 (28.11.97), Full text ; all drawings (Family: none)	1-4
Y	J. Vac. Sci. Technol. B Vol. 15, No. 6, Nov/Dec 1997, Chuan C. Chang, Axcel Scherer, Ron-Chung Tyan, Yeshayahu Fainman, George Witzgall, Eli Yablonovitch "New fabrication techniques for high quality photonic crystals" p.2764-2767, especially p.2764, right column, line 7 to p.2765, left column, line 5; fig. 1. in-plane 2D structure; P.2766, left column, line 31 to right column, line 5, Fig.4	1-4

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
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Date of the actual completion of the international search	Date of mailing of the international search report
01 November, 1999 (01.11.99)	16 November, 1999 (16.11.99)
Name and mailing address of the ISA/ Japanese Patent Office	Authorized officer
Facsimile No.	Telephone No.

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP99/04297

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	The Transactions of The Institute of Electronics, Information and Communication Engineers C-I, Vol. J81-C-I No. 2, (February 1998) Shojiro Kawakami et al., "Mechanism of Shape-Formation for 3D Periodic Nanostructures by Bias Sputtering" p.108-109	1-4
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